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MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

INVESTIGATION OF POTENTIAL DRIVER MODULES AND TRANSMISSION LINES FOR A HIGH FREQUENCY POWER SYSTEM ON THE SPACE STATION

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Date:	August 1, 1986
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ACKNOWLEDGEMENTS

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Finally, I wish to thank Mrs. Jeffery Turner for typing and correcting this report.

ABSTRACT

The objective of this investigation is to assess the feasibility of using Series Resonant Inverter as the driver module for high frequency power system on the Space Station. This study is a continuation from last year. It summarizes the performance of the Series Resonant Inverter that was used in the testing of the single-phase, 2.0-kw resonant AC power system breadboard. This paper also describes the architecture and analyzes the driver modules of the 5.0 kw AC power system breadboard.

An investigation of the various types of transmission lines is continued from last year. Measurements of equivalent series resistor and inductor and equivalent parallel capacitors are presented. In particular, a simplified approach is utilized to describe the optimal transmission line.

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INTRODUCTION

The original Space Station, Skylab, didn't require power at the levels of hundreds of kilowatts. In fact, Skylab used an 8 kilowatt bus for power distribution. In contrast, the Initial Operation Configuration (IOC) Space Station will require 75 kilowatts for primary power distribution while the growth Space Station will require 300 kilowatts. The spacecraft being designed for new NASA missions are projected to have demands for power at orders of magnitude greater than current spacecraft. The evolving spacecraft power systems for these missions will require increased efficiency and versatility to meet load requirements of greater power, multiple users and increased life. Therefore, Space Station must have the ability to be expanded to cover expected power needs of hundreds of kilowatts.

NASA/Lewis Research Center (LeRC) has proposed to use a high-frequency, high-voltage AC power system to fulfill the needs of the Space Station. LeRC, the NASA center responsible for primary power generation and conditioning on the Space Station, proposes to generate the AC power using a resonant AC power system. Furthermore, they are proposing a primary power distribution of 440V AC RMS single phase at 20 kilohertz, and part of this is to be distributed in the common modules.

Marshall Space Flight Center who is responsible for distributing power in the common modules have expressed deep concerns about this AC power system efficiency, transmission reliability, and corona effects inside the module. They have a special concern about using the series resonant inverter as the driver for the power system, and feel that this matter should be resolved before the final decision is made to build the system.

The resonant inverter was tested in a resonant AC power system test program that was developed by General Dynamics, a contractor for LeRC. The test results are utilized to evaluate the performance of multiple resonant inverter driver modules for a 5.0 kw AC power system breadboard.

1.0 SYSTEM TEST CONFIGURATION

1.1 AC System Operation

The basic circuit for the inverter is a simple series resonant circuit as shown in Figure 1-1a. The operation is as follows: When switch S1 is closed, the resonant circuit is excited and "rings" at the natural resonant frequency of the circuit determined by the values of L, R, and C. The voltage across the load will appear as in 1b. The load resistance dissipates energy from the resonant circuit and causes the voltage and current waveforms of the circuit to be damped. If the resonant circuit is now excited from a pair of opposite polarity sources through a pair of toggled switches operating at natural frequency (Figure 2a), a sustained AC wave can be developed as shown in Figure 2b.

This circuit can be implemented in the usual bridge arrangement depicted in Figure 3. Alternatively, the load can be placed in parallel with the resonant capacitor as proposed by Neville Mapham (Figure 4).

The current in the resonant circuit of the inverter is primarily determined by the L and C of the tank circuit. Therefore, the Mapham type inverter is a voltage source device because the load is in parallel with the resonant capacitor. The Mapham inverter is a voltage source but becomes overdamped and begins to operate irregularly for heavy loads. Because the AC breadboard is a utility-type power system the Mapham configuration was chosen as the driver module.

If the resonant frequency of the inverter is increased above the switching frequency then Silicon Controlled Rectifiers (SCRs) can be used as switches. Replacing the load resistor of Figure 4 with a transformer allows the inverter to be used as the driver to a high-voltage bus capable of providing power to a variety of loads. Larger power systems are possible by combining multiple inverter modules.

To test the Mapham topology, a resonant AC series inverter was operated with a DC input voltage and ran through a series of tests to determine its start-up performance, response to load changes, load regulation and efficiency. A summary of the test results is discussed in the following sections.

1.2 Single Inverter (Configuration)

The test configuration was a 1.0 kw inverter module with a resistive load (Figure 5). The inverter schematic is in Figure 6. This module was operated with a 90-volt input and run through a series of tests to determine its start-up performance, response to load changes, load regulation, and efficiency.

2.0 SUMMARY OF TEST RESULTS

2.1 Start-Up of a Single Inverter

The test results indicated that a single inverter in a resonant power system configuration exhibited no problems starting up with a step application of voltage while under no load to 50% resistive-load conditions.

2.2 Steady-State Operation of a Single Inverter Module

The single phase power system breadboard test demonstrated that the resonant inverter was efficient and versatile as a system building block. The 1.0kw inverter breadboard was 96.9% efficient. The inverter supplied power over long distances (50 meters) to active load modules.

The development of inverters must also be continued. Since the majority of the power loss in an inverter was attributable to the SCR's, alternatives must be explored.

2.3 Transient Load Response of a Single Inverter

The inverter circuit is shown in Figure 6 and the circuit used to abruptly change the inverter load is shown in Figure 7. Three load changes were tested:

a. 0.0w to 580w and reverse
b. 580w to 1110w and reverse
c. 130w to 1110w and reverse

The most dramatic power change took place in the 130w to 1110-w case. Yet, the inverter experienced only a short and smooth transition period as shown in Figure 8 and 9, which show the inverter output voltage and current for the 130 to 1110-w and 1110 to 130-w case respectively. Discounting the switch bounce in Figure 8, these figures showed that the overshoot of the inverter was small and the entire transient response lasted only 150 microseconds. The other inverter parameters such as the leg current (Figure 10) also showed a smooth and brief transition for abrupt load changes. The transient response characteristics in the other two cases (0.0w to 580w and reverse and 580w to 1110w and reverse) lasted for a shorter amount of time because the load variation was not as great.

2.4 Power Supply Sensitivity of a Single Inverter

The test results indicated that every parameter in the system showed a smooth transition. The shift to a higher input voltage was also a smooth transition, but its time constant was much longer and was determined by the response time of the power supplies.

2.5 Power Turn Off a Single Inverter

The test results indicated that the output voltage of the inverter merely decayed to zero with a time constant based on the filter components and the load.

2.6 Conclusion

The testing of the single-phase, 2.0-kw resonant AC power system breadboard demonstrated that the resonant inverter was efficient and versatile as a system building block, but it needs to be developed more to get rid of the power losses attributable to the SCR's. Furthermore, the inverter must be more efficient for the AC power system on the Space Station, because it will have to drive high frequency AC power down the boom to the common modules. Therefore, Marshall Space Flight Center, who is responsible for development of power in the common modules, is concerned about using this resonant inverter as the driver for the AC power system.

3.0 MSFC CONCERNS

3.1 Propagation of Fault to Series Resonant Inverter

If a fault in the system propagates back to the SRI, the bus collapses and the system goes dead. MSFC feels that a utility-type power system should be built to provide power to remove fault.

3.2 Efficiency at Partial Loading Due to Redundancy Schemes

LeRC efficiency projections involving SRI are based on full loading. MSFC feels that the projections should be based on 50% loading.

3.3 Corona Effect

For the Space Station, LeRC is proposing a primary power distribution of 440Vrms single phase at 20 kilohertzs. MSFC, who is responsible for the development of the electrical power system in the common modules is concerned about the power distribution in the modules, because the modules are susceptible to corona at high voltage and twenty kilohertz frequency. Therefore, they are planning to reduce the voltage outside the common modules by using a step down transformer.

3.4 The AC Power System Efficiency Dependence

The test results from the 2.0-kw resonant AC power system breadboard indicated that the AC power system efficiency depended much on the resonant inverter efficiency. The test results indicated the efficiency of the power system depended on the frequency of the resonant inverter. That is the efficiency of the system was reduced when the resonant frequency of reactive components and the switching frequency were brought together.

While designing and testing sample transmission lines it was learned that adding the shield to the transmission line increased the resistance and thus the power dissipation of the line. In brief, the efficiency of the system was reduced and this was attributed to the power losses in the transmission line.

Therefore, the AC power system needs more efficient inverters and transmission lines.

Recognizing these needs and concerns, General Dynamics proposed to deliver 5 kw proof of concept AC power processing breadboard to NASA/MSFC for their evaluation in providing common module power.

4.0 AC POWER PROCESSING BREADBOARD ARCHITECTURE

The overall system is shown in Figure II. It features three resonant driver modules with transformer-coupled outputs that may be switched to either of two redundant buses on disconnected from both in case of a module failure. This driver side of the system will be mounted on a single assembly with its control circuitry, microprocessor, and internal power supplies. This assembly will be connected to a receiver assembly with a redundant bus system. Two wuch bus systems will be supplied for seperation distances of 50 or 100 meters. A single receiver assembly will contain its own "load" microprocessor, control circuitry, power supplies, and five transformer-coupled load module. Each will provide different-characteristic outputs and will have the same type of isolation switching as the driver modules, for autonomous fault protection for load faults or internal module failures.

4.1 Analysis of the Driver Modules

Each of the three driver modules will be a series-resonant inverter operating at a frequency of 20 khz. They will be externally synchronized and operate with their outputs connected in a three-phase "Y".

The basic circuit is a series resonant design, that places the load (reflected through the output transformer) in parallel with the resonant capacitor, in the method proposed by Neville Mapham (Figure 4).

This give a system driver that is essentially a voltage source. It has significant advantages for a power system. The line voltage tends to be independent of the load, and it is perfectly happy to be lightly loaded or unloaded just as a utility system should be.

The actual configuration that is currently operating is shown in Figure 12. Of course, the duality of the resonant circuit of this type means that, if the circuit is tolerant of open loads, it is intolerant of overloads and short circuits, particularly in the tyristor-driven configuration pictured. Overloads make the resonant circuit overdamped and, as a result, the current in the on-position thyristors has not decayed to zero before the synchronization pulse requires the other side to turn on. If operated in this mode, a direct power supply short results. The system protects against such faults at two levels.

First, the control circuitry detects the current in the driver branches and inhibits the turn-on signal if it is not correct. Second, the module output switches (or the load switches for a load fault) disconnect the overload, allowing the driver to return to its preferred under-damped mode.

This approach is supposed to be operational on General Dynamic's 2.5 kw IRAD inverter breadboard and its controller. It is supposed to be working.

You can see that here, and throughout the system they have carefully considered fault protection so that the system will meet its internal fail-operational, fail safe goals.

Conclusions and Recommendations

Based on the test results of the AC power system and other factors, MSFC feels that alternate approaches to the SRI modules and transmission lines should be investigated.

Most of my research time has been spent measuring the equivalent series resistor and inductor and parallel capacitor of various wire configurations. The results are shown in Tables 2 through 7. Also, a graph of the transmission line losses is shown in Figure 16. The other part of my research time has been spent analyzing and evaluating the performance of the driver modules in the AC power breadboard test program.

Based on this research, I agree with MSFC that the AC power system should be more efficient before it is built. Therefore, I make the following recommendations.

a) The MSFC AC power breadboard should be used as a test facility.

b) The breadboard should test for fault tolerance, available switching gears and different transmission cable configuration.

c) Time and money should be given engineers to build and test different topologies, in order to improve the SRI drivers efficiency.

TABLE 1

POWER SUPPLY SENSITIVITY OF INVERTER

V_{IN} (V_{DC})	I_{IN} (I_{DC})	V_{OUT} (V_{RMS})	I_{OUT} (I_{RMS})	F (KHZ)
69.9 -20%	10.20	93.0	6.9	20.0
87.0	12.76	117.0	8.2	20.0
104.4 -20%	15.24	140.6	10.2	20.0

TABLE 2

WIRE TEST RESULTS (5 METER LENGTHS)

M18001 *12 (SINGLE INSUL) TWISTED

FREQUENCY (KHZ)	CAP (PF)	ESL (UH)	ESL (MΩ)
0.4	349.1	2.70	70.4
1.0	347.1	2.60	70.4
2.0	346.0	2.50	70.2
4.0	345.9	2.49	71.0
10.0	345.7	2.42	76.8
20.0	345.8	2.36	93.0
40.0	346.1	2.23	132.4
100.0	347.5	2.04	234.3

TABLE 3

WIRE TEST RESULTS (5 METER LENGTHS)

M81044/16 *12 (DOUBLE INSUL) TWISTED

FREQUENCY (KHZ)	CAP (PF)	ESL (UH)	ESL (MΩ)
0.4	205.5	3.09	64.5
1.0	205.0	3.09	64.8
2.0	205.0	3.09	65.1
4.0	205.0	3.08	66.2
10.0	205.9	3.05	72.6
20.0	206.0	2.97	87.9
40.0	206.8	2.87	117.2
100.0	207.8	2.74	206.8

TABLE 4

WIRE TEST RESULTS (5 METER LENGTHS)

SINGLE SHIELD #12

FREQUENCY (KHZ)	CAP (PF)	ESL (UH)	ESL (MΩ)
0.4	1529.9	0.880	122.8
1.0	1528.8	0.798	122.8
2.0	1528.4	0.798	122.9
4.0	1530.6	0.798	123.4
10.0	1529.8	0.774	126.0
20.0	1529.1	0.741	132.6
40.0	1529.1	0.688	145.8
100.0	1529.2	0.629	171.8

TABLE 5

WIRE TEST RESULTS (5 METER LENGTHS)

DOUBLE SHIELD *12

FREQUENCY (KHZ)	CAP (PF)	ESL (UH)	ESL (MΩ)
0.4	1229.6	0.880	72.9
1.0	1228.9	0.862	72.9
2.0	1227.9	0.885	73.2
4.0	1229.4	0.885	73.6
10.0	1228.3	0.866	76.7
20.0	1227.4	0.836	84.3
40.0	1227.2	0.778	100.5
100.0	1227.2	0.704	141.9

TABLE 6

WIRE TEST RESULTS (5 METER LENGTHS)

M22759 *16 (FLIGHT TYPE)

FREQUENCY (KHZ)	CAP (PF)	ESL (UH)	ESL (MΩ)
0.4	178.9	2.85	152.7
1.0	179.0	2.89	152.7
2.0	179.0	2.87	153.2
4.0	179.4	2.87	153.5
10.0	180.0	2.85	158.1
20.0	180.5	2.81	172.2
40.0	180.2	2.73	210.5
100.0	182.4	2.51	309.5

TABLE 7

WIRE TEST RESULTS (5 METER LENGTHS)

SINGLE SHIELD #16

FREQUENCY (KHZ)	CAP (PF)	ESL (UH)	ESL (MΩ)
0.4	1226.6	0.89	216.2
1.0	1225.4	0.91	216.7
2.0	1224.8	0.91	216.7
4.0	1226.3	0.92	216.7
10.0	1225.2	0.92	217.9
20.0	1224.3	0.91	221.8
40.0	1224.1	0.88	234.4
100.0	1224.0	0.82	273.3

TABLE 8

WIRE TEST RESULTS (5 METER LENGTHS)

DOUBLE SHIELD #16

FREQUENCY (KHZ)	CAP (PF)	ESL (UH)	ESL (MΩ)
0.4	1229.6	0.99	134.7
1.0	1228.5	1.00	134.7
2.0	1228.6	1.00	134.8
4.0	1229.4	1.00	135.0
10.0	1228.3	1.00	136.6
20.0	1227.4	1.00	141.8
40.0	1227.2	0.99	159.1
100.0	1227.3	0.90	220.3

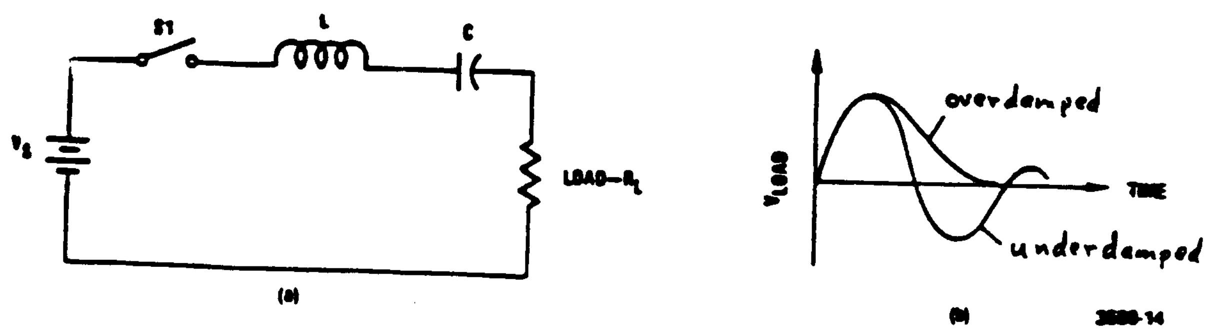


Figure 1. Basic Series Resonant Circuit

Figure A-1. Basic resonant circuit.

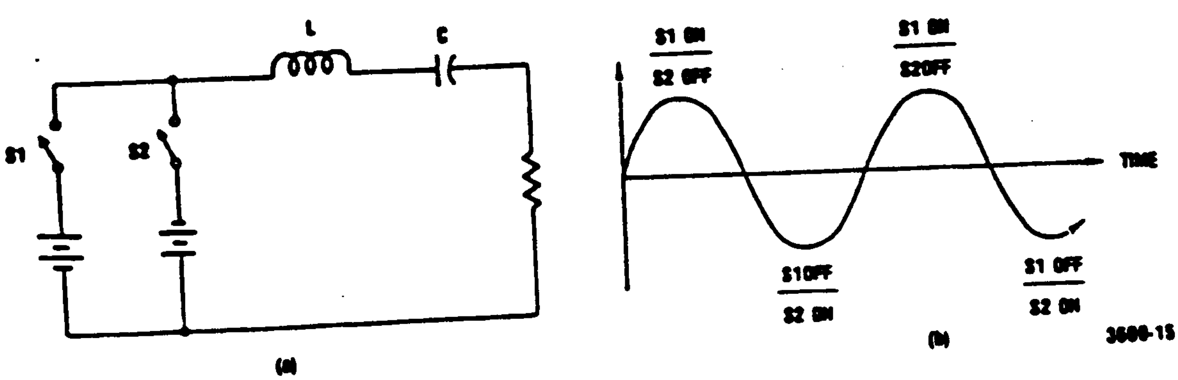


Figure 2. Dual-Polarity Series Resonant Circuit

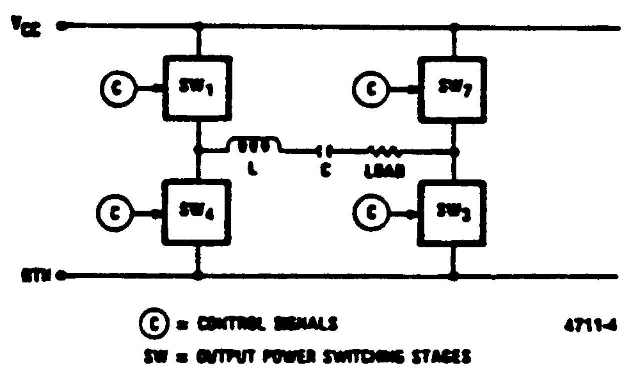


Figure 3. Series - Output Type Series Bridge Circuit

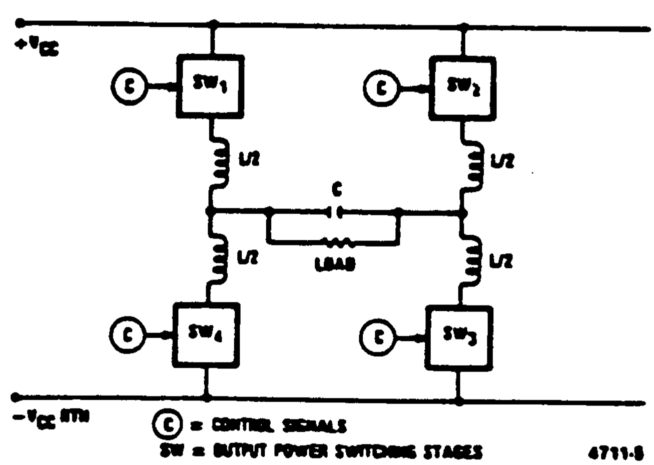


Figure 4. Parallel - Output Type Series Resonant Bridge Circuit

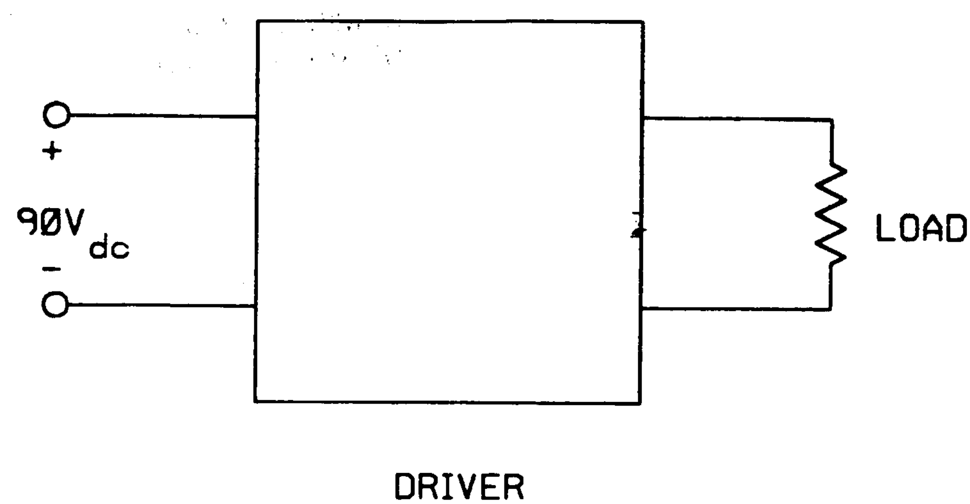


Figure 5. Test Configuration Driver with Resistive Load

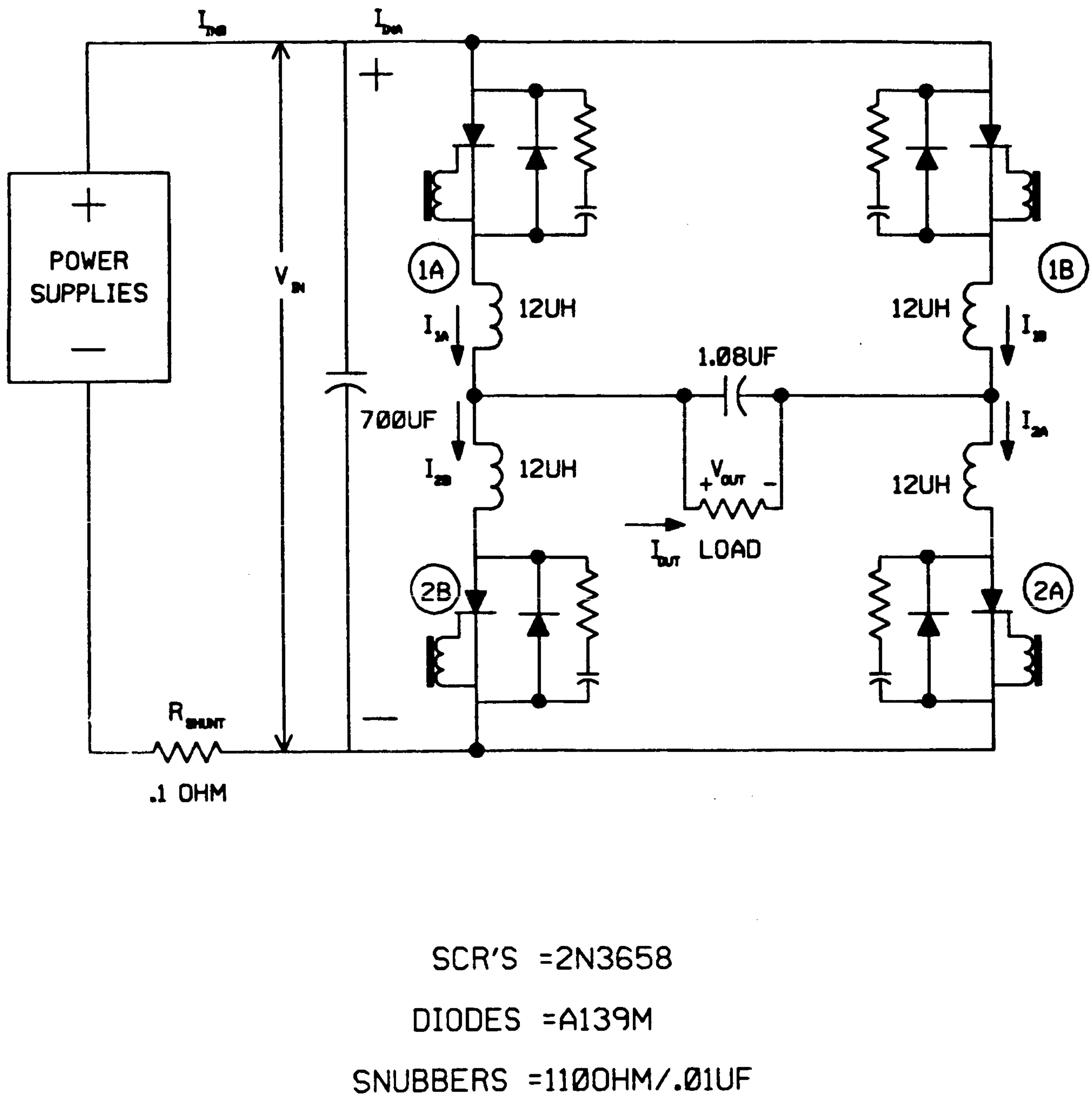
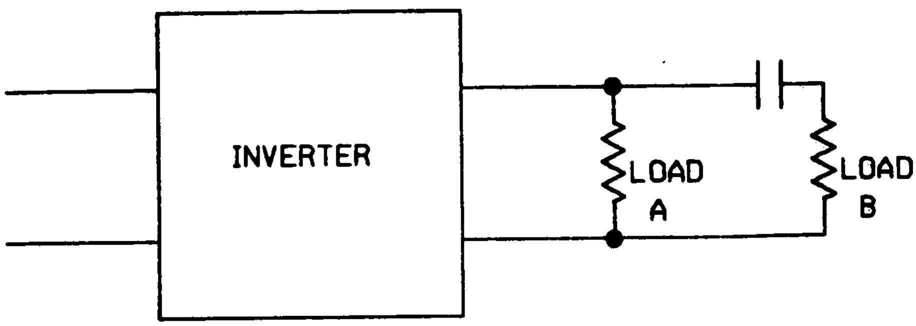


Figure 6. 1.0kw Inverter Schematic



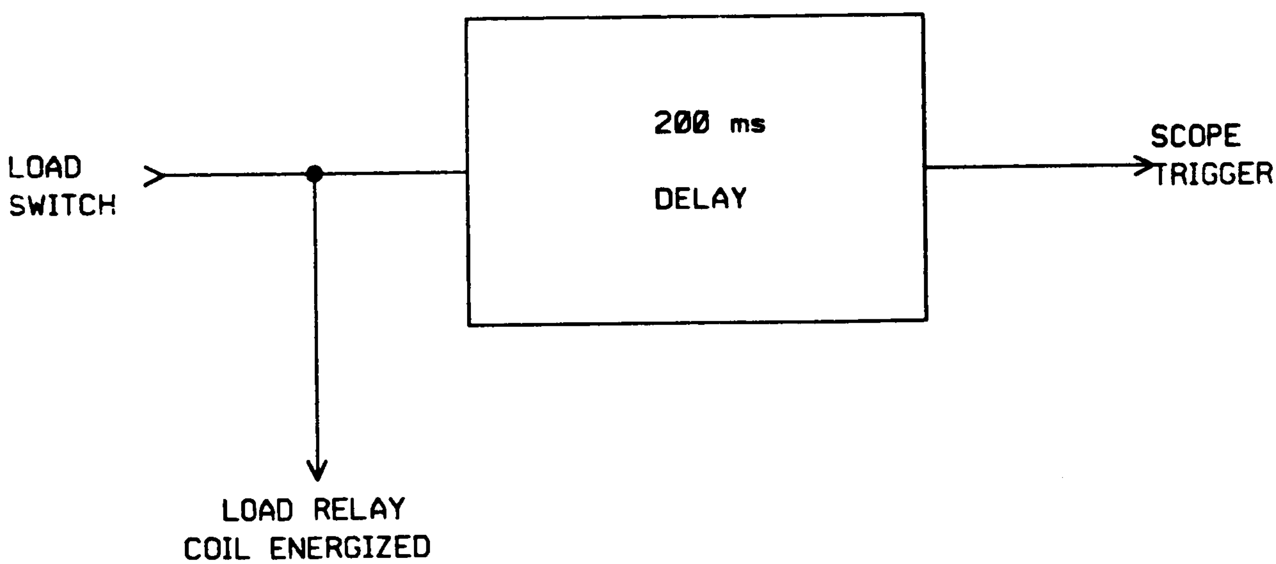


Figure 7. Test Circuit to Measure Transient Load Response of a Single Inverter Module

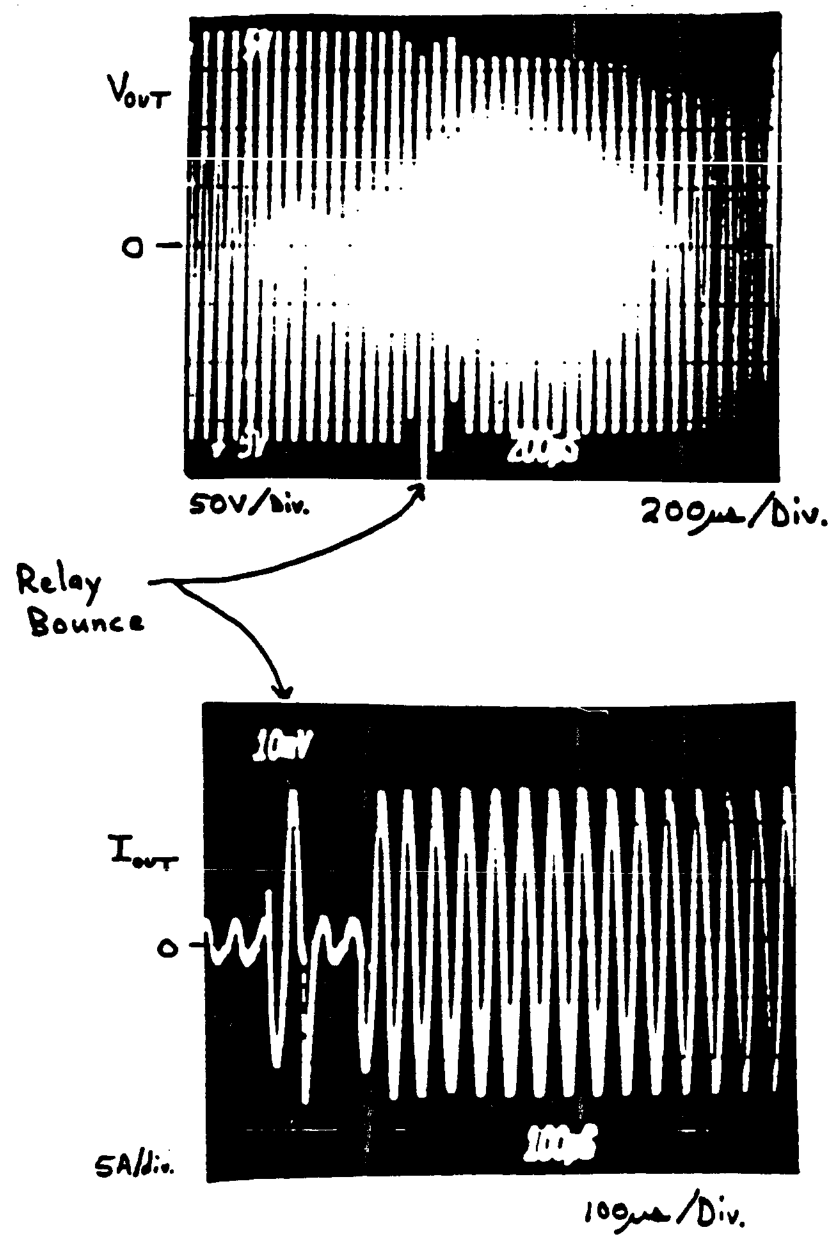


Figure 8. Inverter Output Voltage and Current as the Load is Switched from 130w to 1110w

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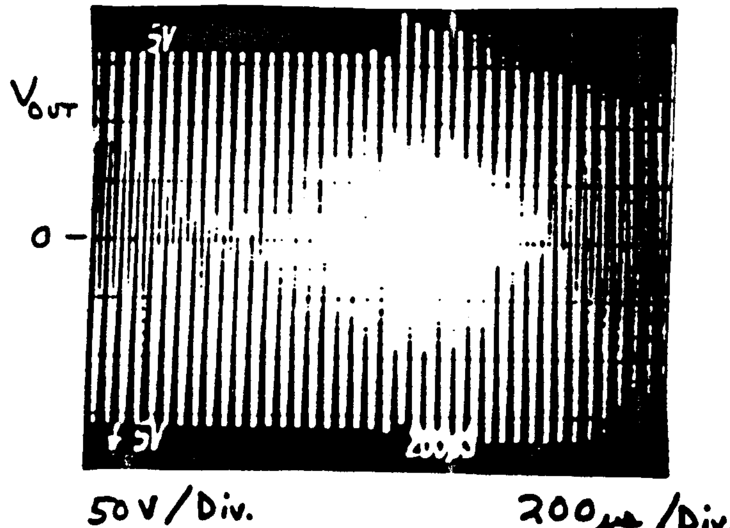

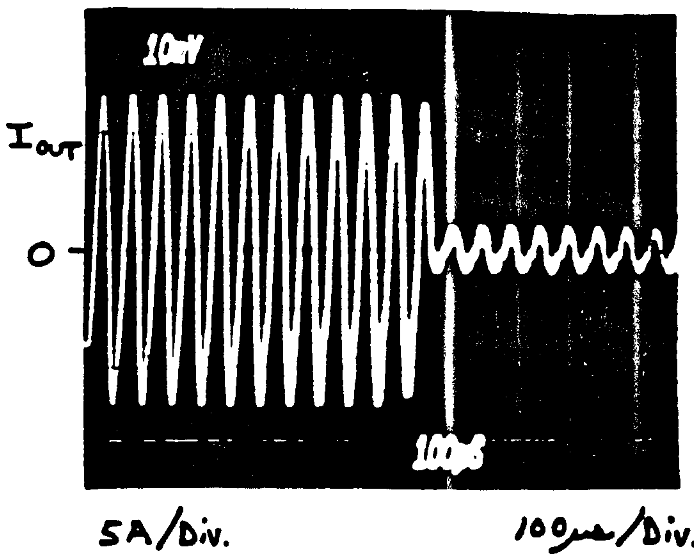

Figure 9. Inverter Output Voltage and Current as the Load is Switched from 110w to 130w

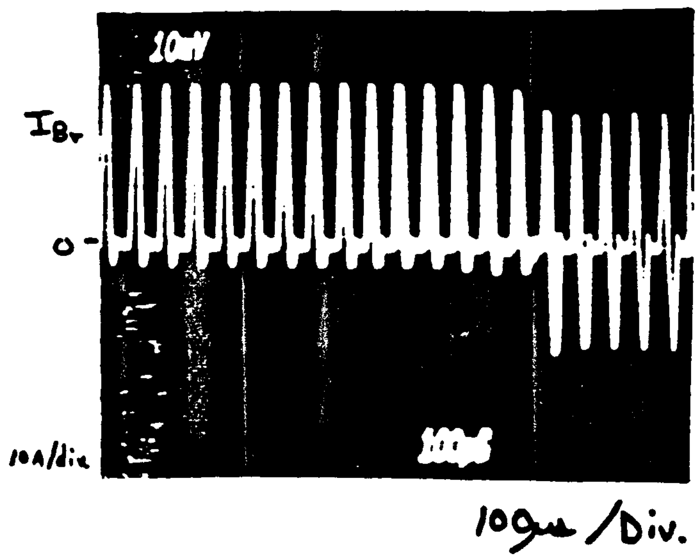

Figure 10 Inverter Leg Current as the Load is Switched from 110w to 130w

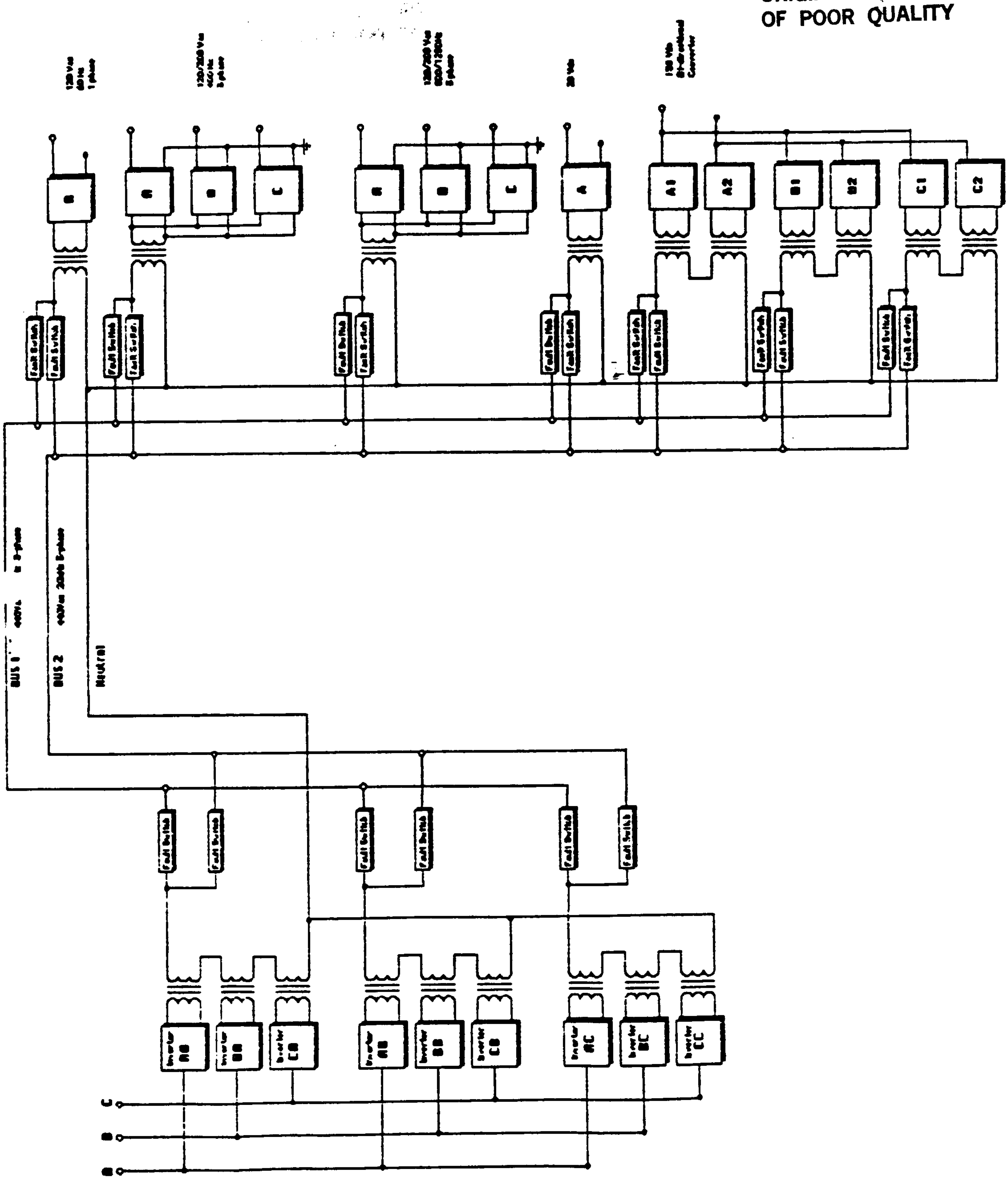

FIGURE 11 AC. BREADBOARD

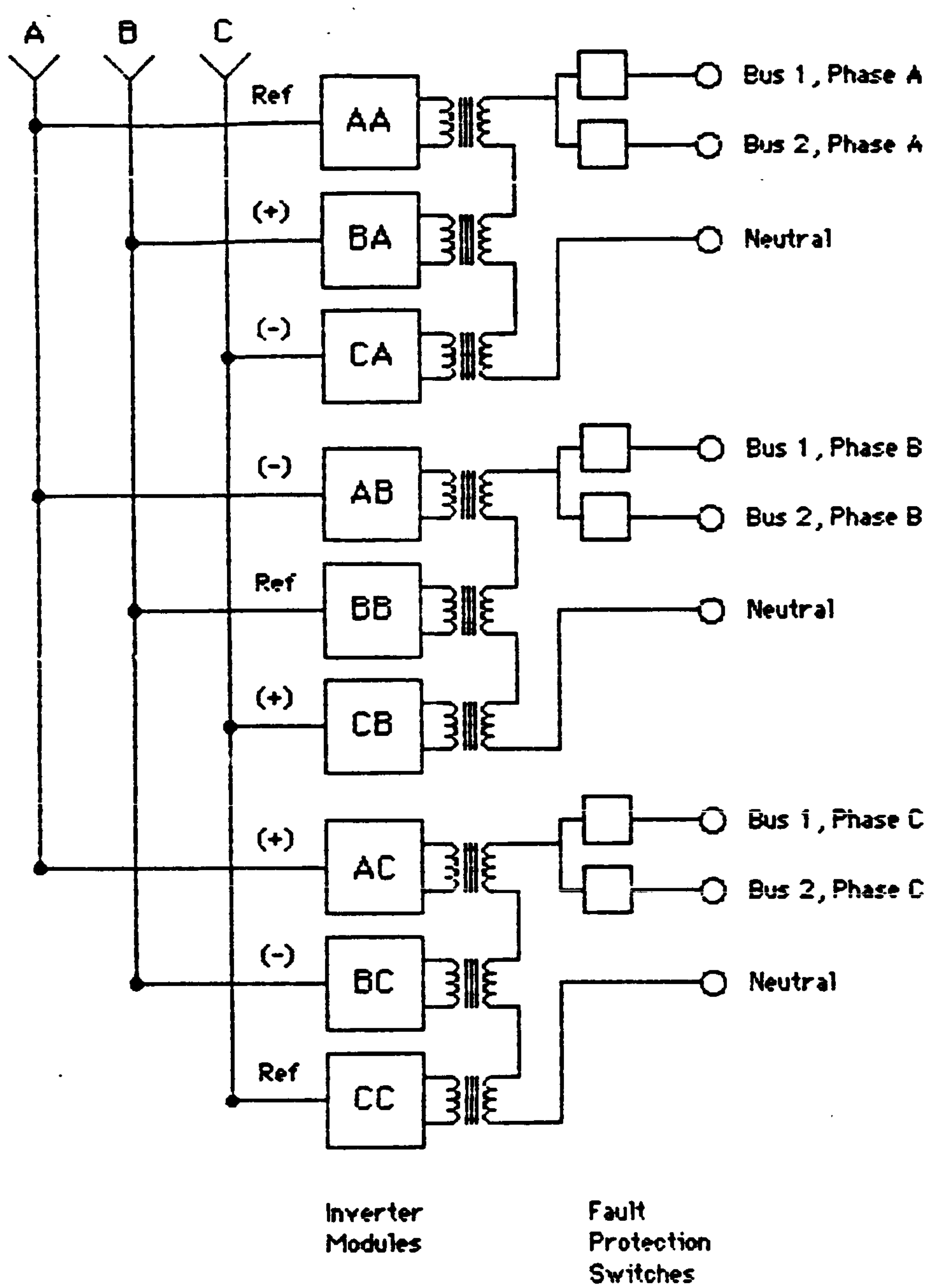

FIGURE 12   9 INVERTER MODULES

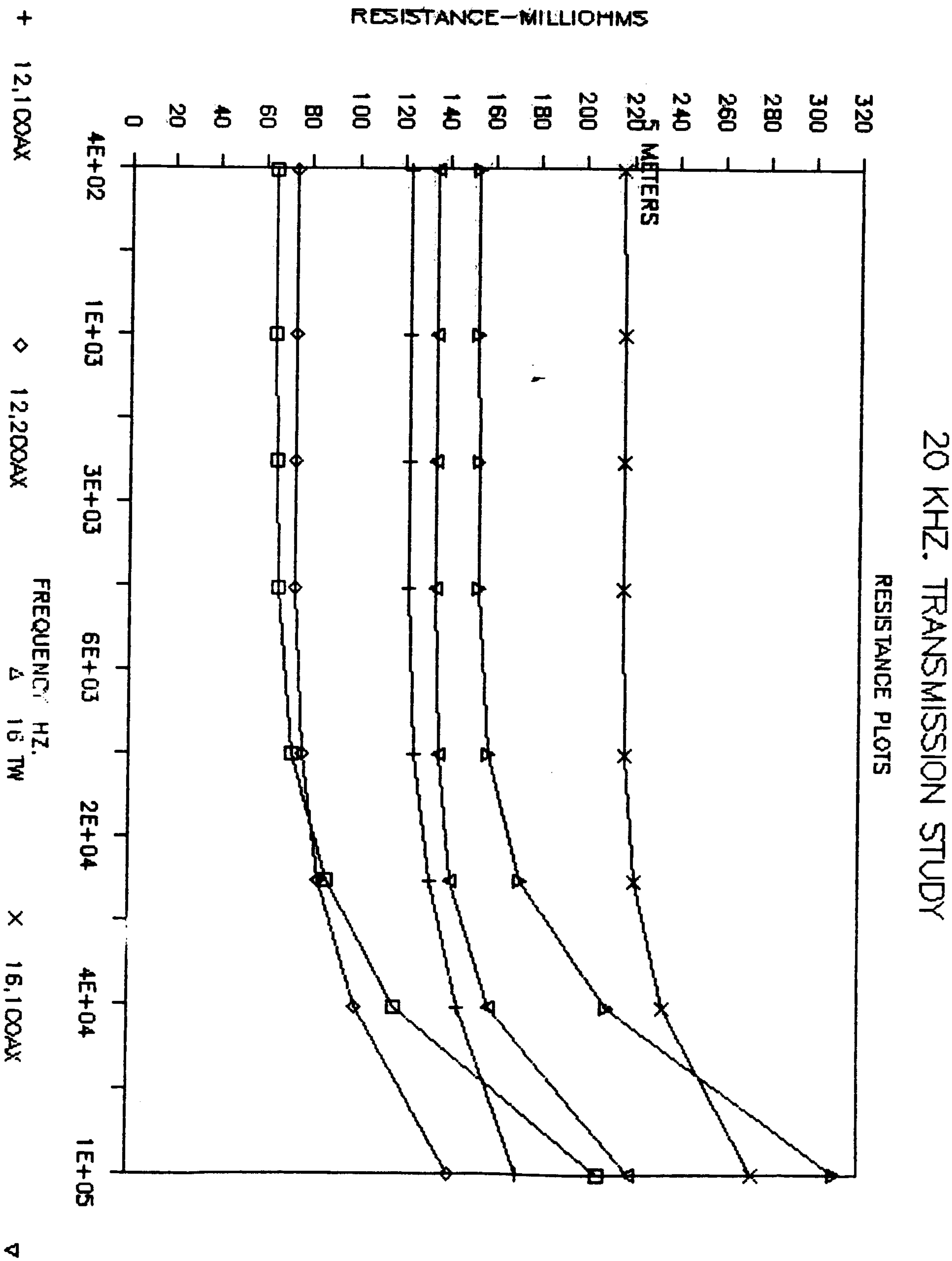
20 KHZ. TRANSMISSION STUDY
RESISTANCE PLOTS
RESISTANCE—MILLIOHMS
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
5 METERS
4E+02
1E+03
3E+03
6E+03
2E+04
4E+04
1E+05
FREQUENCY HZ.
+ 12.1COAX
◇ 12.2COAX
Δ 16 TW
× 16.1COAX

FIGURE 13

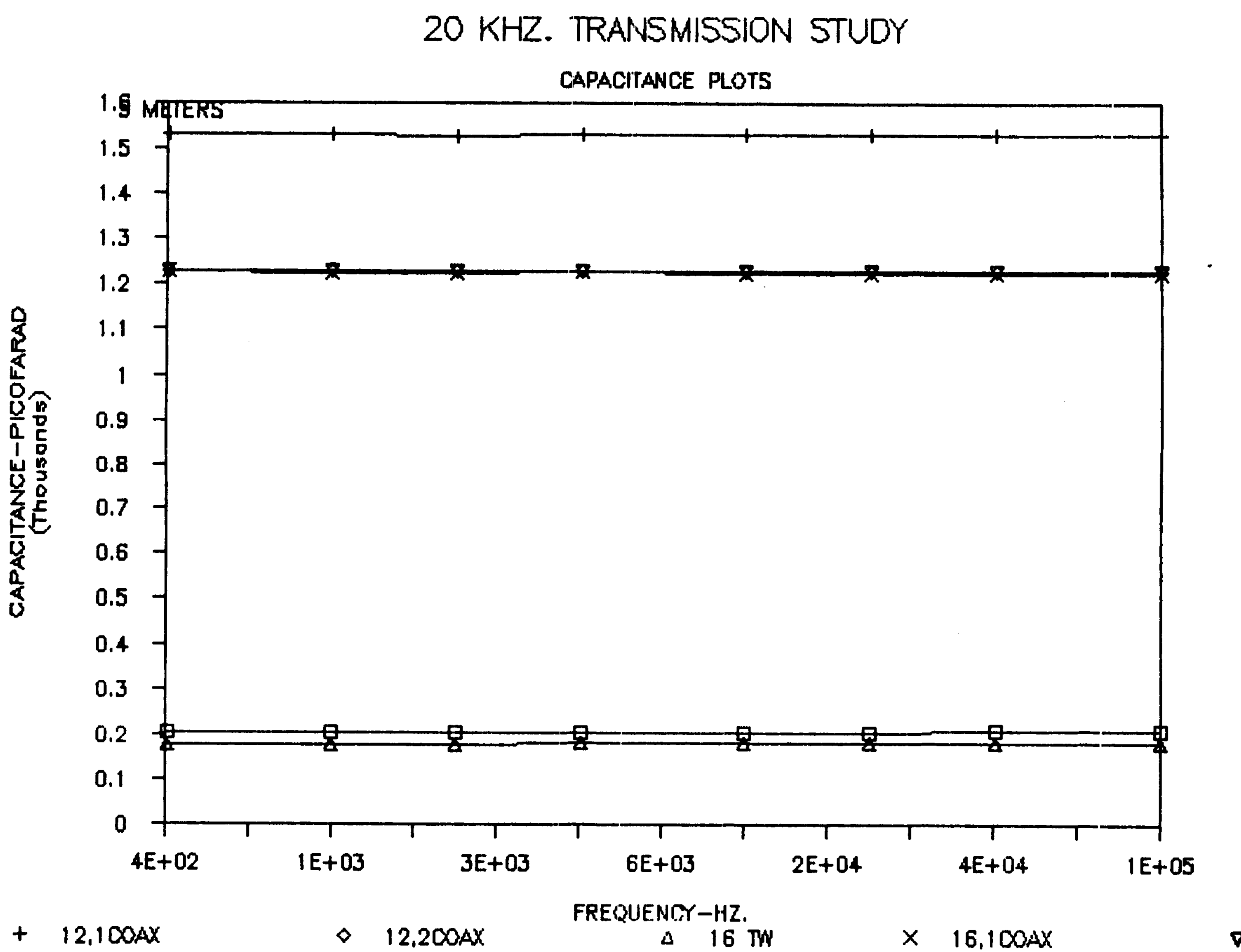

FIGURE 14
XI-29

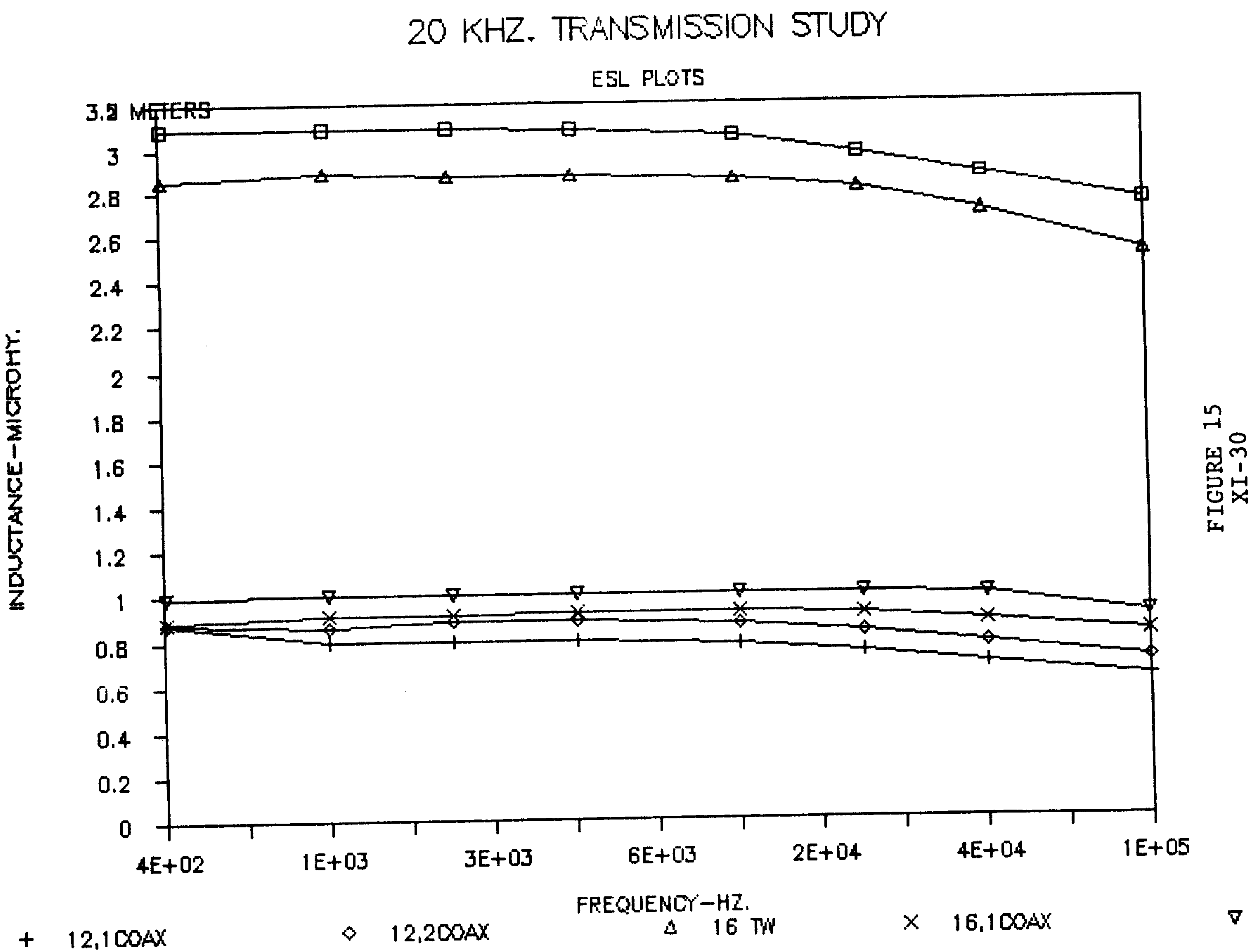

FIGURE 15
XI-30

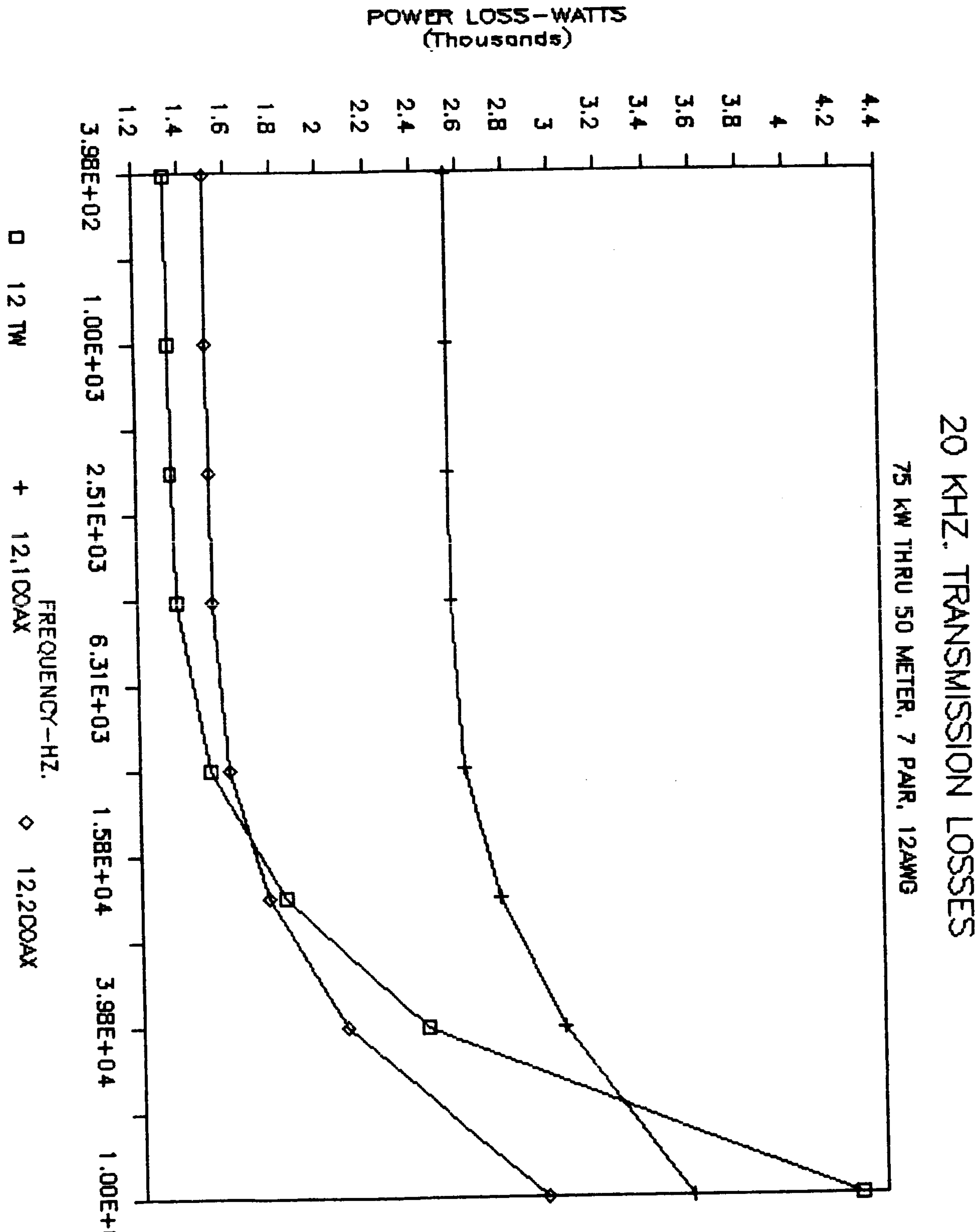
20 KHZ. TRANSMISSION LOSSES
75 KW THRU 50 METER, 7 PAIR, 12AWG
POWER LOSS-WATTS
(Thousands)
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
4.2
4.4
3.98E+02
1.00E+03
2.51E+03
6.31E+03
1.58E+04
3.98E+04
1.00E+05
FREQUENCY-HZ.
12 TW
12.1COAX
12.2COAX

FIGURE 16

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